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Stability and Support Issues in the Construction of Large Span Caverns for Physics

Laughton, C.

Fermi Research Alliance, Batavia, Illinois, United States of America

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ABSTRACT: New physics experiments, proposed to study neutrinos and protons, call for the use of large underground particle detectors. In the United States, such detectors would be housed in the US Deep Underground Science and Engineering Laboratory (DUSEL), sited within the footprint of the defunct Homestake Mine, South Dakota.

Although the experimental proposals differ in detail, all rely heavily upon the ability of the mined and reinforced rock mass to serve as a stable host for the detector facilities. Experimental proposals, based on the use of Water Cherenkov detector technology, specify rock caverns with excavated volumes in excess of half a million cubic meters, spans of at least 50 m, sited at depths of approximately one to 1.5 kilometers. Although perhaps sited at shallower depth, proposals based on the use of Liquid Argon (LAr) detector technology are no less challenging. LAr proposals not only call for the excavation of large span caverns, but have an additional need for the safe management of large quantities (kilo-tonnes) of cryogenic liquid, including critical provisions for the fail-safe egress of underground personnel and the reliable exhaust of Argon gas in the event of a catastrophic release. These multi-year, high value physics experiments will provide the key experimental data needed to support the research of a new generation of physicists as they probe the behavior of basic particles and the fundamental laws of nature. The rock engineer must deliver caverns that will reliably meet operational requirements and remain stable for periods conservatively estimated to be in excess of twenty years.

This paper provides an overview of the DUSEL site conditions and discusses key end-user requirements and design criteria likely to dominate in determining the viability of experimental options. The paper stresses the paramount importance of collecting adequate site-specific data to inform early siting, dimensioning and layout decisions. Given the large-scale of the excavation and likely timeline to construction, the paper also strongly suggests that there are exciting opportunities for the rock mechanics and engineering community to identify and efficiently integrate research components into the design and construction process.

1. INTRODUCTION

The Deep Underground Science and Engineering Laboratory (DUSEL) is a new facility dedicated to underground research. DUSEL brings together a diverse group of science and engineering partners to plan and perform a new generation of scientific and engineering experiments.

Since its conception in the early 2000's the DUSEL initiative has generated a great deal of interest amongst key underground research communities (physics, biology, geosciences, engineering). Approximately one hundred research proposals have already been submitted, including several that represent the early fruits of synergistic collaboration between the partner disciplines.

To accomplish the diverse goals of DUSEL, multi-level occupancy is planned with laboratory clusters sited at depths from a hundred meters to roughly two and an half kilometers below surface. These underground campus facilities will be largely self-sufficient, with space provided for laboratories, workshops, offices and access to site-wide infrastructure. In addition, outpost facilities may be strategically developed to provide for drilling and sampling in areas of particular geologic and biologic interest. Rock mass structures may also be isolated under user-controlled conditions to study topics of particular interest to the earth science and rock mechanics communities, e.g., water flow in fractured aquifers and rock mass behavior under stress.

DUSEL will specifically offer underground engineers sterling opportunities to test new instrumentation, equipment methods and materials, both as an integral part of the DUSEL design and construction process and as an independent research task.

Most typically, underground physics laboratories have been built adjacent to excavated sites, e.g., mine and road tunnels. These laboratories benefit from facility expertise and shared management, construction, access and infrastructure costs, but suffer the constraints that junior partnership entails. Unlike these parasitic laboratories, DUSEL will be built for, and dedicated to, research. To support the program, half a billion dollars has been identified for construction and operation [1]. This budget will enable the reopening of the Homestake mine to its full depth and support a number of high priority research initiatives in the basic and applied sciences. The multi-disciplinary nature of the partnership will allow a breadth of research and economy of scale that is unrivalled by other underground research ventures.

DUSEL will provide a wide range of exciting opportunities for frontier research to both advance our fundamental understanding of nature and contribute to a broad improvement in the state-of-the-art in hard rock engineering.

2. THE US DUSEL SITE

2.1. The Homestake Mine

DUSEL is sited within the boundaries of the recently closed Homestake Gold Mine in the town of Lead, South Dakota. Lead is located in the Black Hills, some 60 km northwest of Rapid City.

Ore was extracted from the Homestake Mine for well over one hundred years prior to its closure in the early 2000's. Within the mine volume, there are over 500 km of development and haulage tunnel and a network of vertical shafts and ramps that extend down some 2,400 m below surface (Figure 1).

On-going preliminary design and rehabilitation work is being led by a management team of physicists and engineers from the University of California and the South Dakota Science and Technology Authority (SDSTA). SDSTA is responsible for re-opening the mine to the 4850 level and supporting an initial experimental phase of laboratory operation. Levels are designated based on the number of feet below surface.

The full DUSEL will be constructed with funding from the National Science Foundation (NSF) and includes plans to further develop laboratory space, including campus sites and research outposts down to the bottom of the mine at the 8000 level.

Figure 1: Homestake Mine Headhouse

The shallowest research site (300 Level) will be accessed though a drive-in portal. Intermediate and deep levels will be accessed and ventilated using the existing network of vertical shafts, winzes and ramps.

The start-up research program at 4850 will be developed as an "Initial Suite of Experiments" (ISE) starting towards the end of the decade. The ISE is not yet selected, but will likely include a core physics program and potentially a number of satellite experimental stations sited at both shallow and intermediate depth.

The NSF is sponsoring the preliminary design work with construction funding for access to the deepest levels currently planned to start in 2012.

2.2. Site Characterization

During the life of the mine, ore-bearing units, and hanging wall and footwall contact zones were extensively core-drilled, sampled and mined. Rock units, grades and other salient data sets related to the mining economics were studied in detail. A core library was developed and is stored on-site. The geologic information has also been well-documented within an industry-standard 3-D data base and graphics package.

A good deal of information on engineering properties, in situ loading and ground mass behavior was also obtained and analyzed during the latter stages of mine operation. This information was used to support planning in the more challenging areas of the mine. Specific studies were conducted to evaluate seismic events and assess stability of critical structures. Technical reports were produced that addressed a number of engineering topics.

The spatial data sets and studies conducted during mining can be accessed for further development by scientists and engineering researchers seeking specific ambient conditions or targets of opportunity for in situ research. In particular, for rock engineering purposes, the availability of the 3-D data base, technical reports and related seismic, maintenance, mining and stoping records can offer valuable lessons learned and provide key insight in to the mechanics of rock mass behavior at the site.

These sets of historic mine data, used in combination, will provide a solid foundation and starting point upon which to build in planning for and conducting the site investigation, rock mass characterization, and design work for refurbished and new DUSEL openings.

2.3. *Mine Geology*

The Homestake Mine is sited in metamorphic rock units, primarily schists, phyllites and amphibolites. The main rock units mined at Homestake were the Poorman, Homestake and Ellison [2]. These formations are sedimentary in origin, but since deposition have been subjected to extensive deformation, as can be surmised from the cross-sectional structure shown in Figure 2. These deformed units were subsequently intruded by cross-cutting structures.

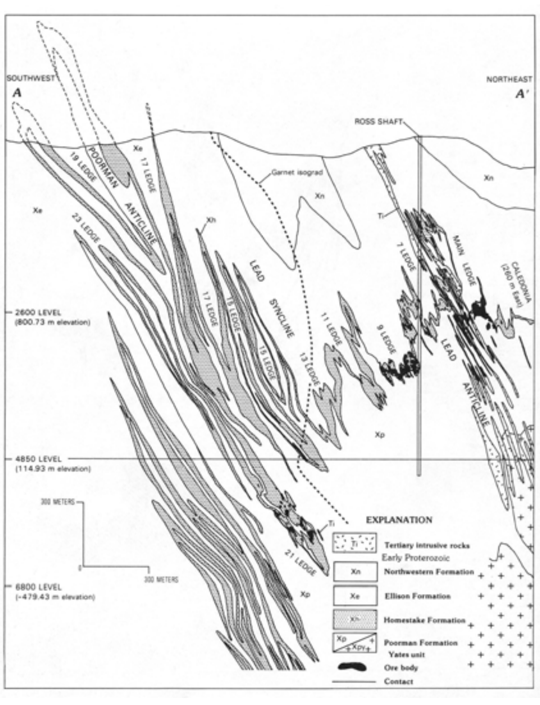

Figure 2: Geologic Cross-section, (Source: http://homestake.sdsmt.edu/HRB/Refer.htm)

The complexity of the host geologic structure provides a key insight into one of the factors that will be a critical consideration in the planning of site investigation and characterization work for DUSEL -- variability. Intact strength, stress, fracture and water conditions may all be expected to vary markedly within and between rock units.

2.4. *Intact Strength Range*

Pfarr [5] notes a uniaxial compressive strength range for the host rock units of 130 to 200 MPa. The lower strengths values were registered in the less competent rocks, encountered in lower mine levels. Other representative uniaxial compressive and tensile strength values posted on the DUSEL website highlight the variation in strength both from unit to unit and as a function of loading direction relative to schistocity.

Although outside of the mineralized zone, and thus less well investigated, the Yates schist formation may offer superior intact and mass strength qualities compared to the three better-characterized units and is being considered as a candidate host rock for some of the larger caverns described below.

2.5. *Discontinuities*

The DUSEL host rock mass contains a range of structural features including jointing, fracture zones, and intrusions. These features, acting individually or in combination, can all be expected to have a significant influence on the comportment of the excavated rock mass across the DUSEL site.

Delineation of major through-going structures and joint sets at an early point in the project planning process will be a fundamental step towards identifying "stay-away zones" and, by a process of elimination, potential "best sites" in which to locate more demanding DUSEL physics excavations.

2.6. *Groundwater*

Water bearing fracture zones were intersected during mining. These "watercourses" were often associated with fracture zones, and locally yielded hot water under pressure.

On a mine-wide basis, steady state pumping during the latter years of operation was on the order of 2700 l/min [3]. Since mining operations ceased and the pumps were turned off, the water level in the mine has risen from the 8000 sump level to above the 5000 level. Pumping of the upper levels will be recommenced once a network of sumps, pumps and piping are reestablished to depth.

2.7. *In Situ Stress*

In addition to strength, discontinuity and water inflow data, good quality data on the state of in situ stress was acquired during the latter years of mine operation. Of particular note are underground campaigns that allowed for estimates of the in situ stress profile as a function of depth and orientation relative to the geologic structure, as recently reported by Tsarik et al. [5]:

$$\sigma v = 0.028 * Z$$

$$\sigma h_1 = 14.328 + (0.012 * Z)$$

$$\sigma h_2 = 0.834 + (0.012 * Z)$$

where Z = depth in meters

σv = vertical stress, MPa

σh_1 = horizontal stress along dip, MPa

σh_2 = horizontal stress along strike, MPa

In situ testing has identified zones of overstress and stress variation across geo-material boundaries. Specifically, Johnson et al. [6] attributed core disking on the 3650 level to overstress in the rock bounding the mined excavation. Girard et al [6] attributed local variation in stress to stiffness contrasts between geo-units.

Based on values of stress and strength noted above, miners are likely to find that issues of overstress increasingly dominate cavern stability at depth. Locations, shapes, and orientations of openings and multi-pass excavation sequencing may increasingly become the key design considerations.

At DUSEL the spatial variability observed in rock strength, structural regime and stress underline the necessity to investigate the rock mass conditions on both mine-wide and site-by-site bases.

2.8. *Mine Excavation Behavior*

For many of the physics experiments, a high premium will be placed on maintaining the stability of the excavations for long periods. Stability will not simply be an issue of preventing large falls of ground. In heavily occupied or trafficked areas, it will also mean eliminating minor falls and limiting long-term deformation. Small falls and/or large convergence in experimental areas would not only require repair but could also interrupt research programs, and damage equipment. Even in tunnels repair can be a significant on-going cost. At the Asop Laboratory annual maintenance costs averaged over one percent of the capital cost [8].

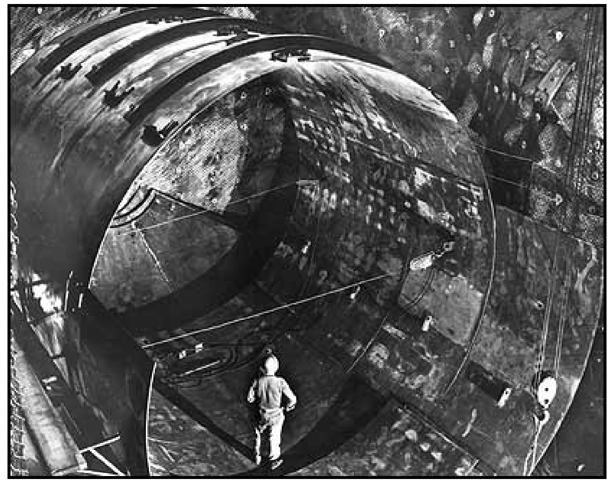

Figure 3: Homestake's First Neutrino Detector (Source; Brookhaven National Laboratory)

For experimental areas excavated at intermediate and deep sites, the potential for long-term deformation under conditions of yield or burst must be thoroughly investigated.

Long-term deformation plots obtained from extensometers installed in a 3650 level stope indicate a significant time-dependent component to rock behavior [9]. Confinement, through support, will be necessary to arrest convergence and reach a stable equilibrium that can be reliably maintained for the cavern's full working life. Knowledge of the host rock's long-term behavior and quantification of the forces required to maintain long-term stability will be necessary before practical support plan can be developed with confidence. Further measurements of the extensometer set installed on the 3650 would be a great first step in this process.

As noted earlier, the Yates formation is being considered as a host rock for large caverns. The Yates already houses a small (10 m span) physics chamber, shown in Figure 3. As reported, the intact Yates is significantly stronger than other rock units. However, Tsarik et al raise the concern that the Yates formation could have rock burst potential, if overstressed, noting "The high strength of the laboratory specimens combined with their elastic-brittle behavior when loaded to failure indicate that the Yates rock may be prone to bursting". Another issue to investigate going forward.

3. LARGE CAVERNS FOR PHYSICS

3.1. *The Long Baseline Program*

The US High Energy Physics community is currently charting the direction for a new era of experimental physics. The plan is likely to include, if not spotlight, the development of a world class neutrino program. A cornerstone element of this plan would be a Long Baseline Experiment.

In rock engineering terms, this experiment can be succinctly characterized as including the construction of a new neutrino beamline tunnel at Fermilab and caverns at DUSEL [10]. Physics caverns being considered for the Long Baseline could be significantly larger than any others previously constructed at other underground sites (European Particle Physics Laboratory, Sudbury Neutrino Observatory, Gran Sasso, Kamioka Mine). The balance of this paper will discuss some engineering challenges associated with designing and constructing such Megacaverns at depth.

3.2. End-User Requirements

In many respects, end-user requirements for underground physics caverns are similar to those demanded by other users of permanent underground facilities where routine personnel access is required, including: long-term stability of the structure, access and operating space for personnel, equipment and infrastructure, anchors, corrosion protection measures, water control, utility runs, environmental protections, and, most importantly, safe refuge and egress provisions.

The physics end-user may impose additional requirements relative to: excavation alignment, cleanliness (surfaces and air), radioactivity thresholds for host rock and imported concrete, shielding of imported radiation sources, radon gas exclusion, watertightness, climate control, and foundation movements.

Long Baseline Megadetectors will add particular requirements to create large-deep space, with excavated volumes in excess of half a million cubic meters, free spans of up to 70 meters, built at depths of up to 1.5 kilometers. In addition, detectors based on the use of Liquid Argon (LAr) detection technology may be built at shallower depth, but still call for similar spans to be excavated and additionally require the failsafe storage of large quantities of cryogenic fluid, to include provisions for the safe egress of personnel, exhaust of Argon gas, and freeze-protection of permanent structures in the event of a catastrophic release.

4. CAVERN DESIGN CRITERIA

4.1. Overview

A number of cavern options have been proposed by the physics community to house a Long Baseline detector at the DUSEL site. The following text concentrates on a discussion of potential cost drivers associated with two of several options suggested to date; a Liquid Argon Detector Cavern at the 300 Level and a Water Cherenkov Detector Cavern at the 4850 Level.

4.2. LAr Cavern at 300 Level

Liquid Argon (LAr) detectors have some distinct advantages over their main rival, water Cherenkov detectors. Most notably they can operate effectively at shallower depths and smaller quantities are required to attain the same detector performance. However, before large LAr detectors can be adopted for underground research, it will be necessary to demonstrate that the host facilities can reliably meet safety imperatives for the safe evacuation of personnel and the exhaust of Argon gas in the event of a catastrophic release.

Initial engineering concepts for the underground storage of large quantities of LAr draw on experience from the Liquid Natural Gas industry and recent tunnel ventilation designs being adopted in new or retrofitted rail and road tunnels. A cross-section for a low-cover cavern is shown in Figure 4.

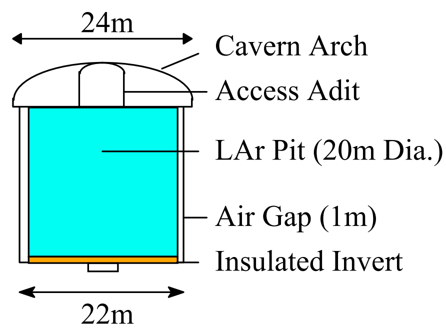

Figure 4: Low Cover LAr Cavern

At shallow depth it is anticipated that cavern design will prioritize the mitigation of block and wedge fall-out under gravity loading. The initial conceptual layout has focused on improving crown stability by aligning the arch to be sub-perpendicular to the direction of the maximum horizontal stress and the strike of dominant planes of weakness.

4.3. Water Cherenkov at 4850 Level

With the additional earth shielding provided at the 4850 level, both LAr and Water Cherenkov technologies could be used to support a parallel research effort into the study of neutrinos (Long Baseline) and protons (Proton Decay). At this depth it is anticipated that the design will need to consider both the blocky nature of the rock and the impact of the in situ stress regime on the short and long-term excavation stability.

The selection of potential sites and the collection of site-specific data are critical if the design of any of the Megacavern proposals are to be advanced beyond what is, at present, a highly speculative conceptual phase.

5. A RATIONALE FOR RESEARCH

5.1. Building a Better Cavern

Although megacavern designs are in their infancy, *a priori*, there appears to be no intrinsic reason why one or multiple megacaverns cannot be built at DUSEL. However, as the author hopes has become apparent from the discussion above, the challenges associated with their construction are not insignificant. The cost of the construction work is likely to be a major component of the experiment's budget and may determine whether the experiment is funded or not. Long Baseline and Proton Decay protagonists have a vested interest in supporting the early advancement of the cavern investigation and design work and, potentially, research aimed at reducing cost and duration.

Below is a cost and schedule exercise undertaken to identify the cost drivers associated with the excavation of a "medium-sized" physics cavern at the 300 Level of DUSEL.

5.2. Cost to Construct

Table 1 summarizes an order of magnitude (OM) construction cost for a 24 m span LAr cavern and associated structures. The costs are based on unit pricing taken from the estimate of a similar underground experiment proposed for construction in central California. The costs were developed by an experienced estimator familiar with public contracting practices. Direct and indirect costs, insurance, bonding, and profit margin were all included in the bid price.

Costs include all rock lining (shotcrete) and invert concrete, to provide for the delivery of a shell ready for electrical, mechanical and technical installation.

Given the absence of site investigation data and limited engineering time devoted to this exercise, the set of costs is highly generic, but they do provide a framework for an early discussion of value engineering and research opportunities.

Table 1; LAr Cavern OM Estimate

Cost Item	Cost, $k
Mobilization/Demobilization	3,000
Portal Construction	250
160 m of Access Tunnel (6m HS)	225
16 m Vertical Shaft (~6 m dia.)	500
30 m Horseshoe Cavern (24m span)	2,000
20 m Deep Detector Pit (~22 m dia.)	3,500
Concrete Floors (30 cm)	600
Total	10,075
Total with AE/CM Cost @ 20%	12,090

At this early point in a project's development a realistic evaluation of underground contingency is critical. Contingency is a key communications tool in any underground project. The number is initially likely be large, and draw management attention to the influence that risk can have on the viability of the project. The need for identification and mitigation of risk will become self-evident, and provide the impetus for management to decide to invest early project dollars in site investigation, characterization and design work.

5.3. LAr Cavern - Risk to Construct

The estimate presented here is based on untested geo-hypotheses and engineering experience on similar projects. More objective and global assessments of project risk will be needed once more site-specific data is gathered and a scope established. In the meantime, a brief explanation for the allocation of upper contingency values is outlined, based on Sperry's risk categories [12];

Geotechnical Risk: The underlying engineering assumption is that rock mass behavior will be uniformly good. Rock stabilization will be achieved using rock bolts and shotcrete without recourse to extraordinary rock treatment or support measures. There is no site investigation data to either support or refute this assumption.

Estimating Risk: The estimate is a simple extrapolation of an existing estimate. However, scope of work (portal, tunnel, cavern), methods and means (drill and blast), and productivity rates should be similar.

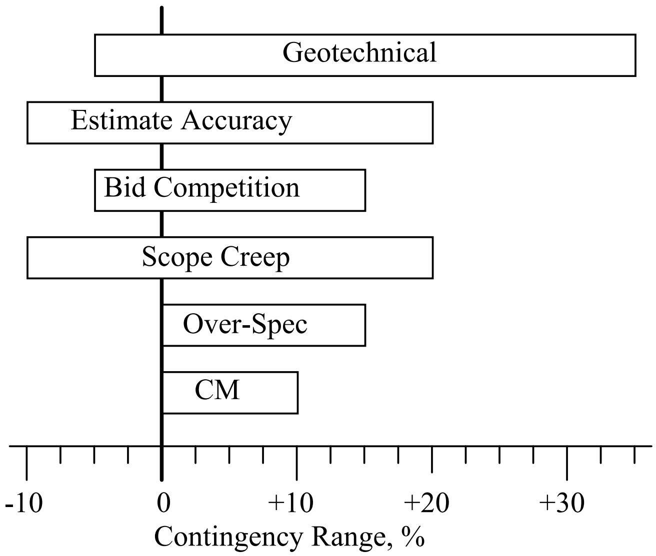

Figure 5: Contingency Ranges for OM Estimate

Bid Competition Risk: Market conditions are reportedly unfavorable. Contract mining and underground construction companies are busy.

Scope-Creep Risk: There may be opportunities for reducing cost, but additional mitigation measures may well be introduced, after review by others.

Over-Specification Risk: The basis of estimate assumes standard industry practice. Challenging end-user demands could raise costs substantially.

Construction Management (CM) Risk: Problems during construction could increase management costs.

Adding the upper or worst case contingency values (%) for the above five categories yields a contingency of over one hundred percent and a budget value for the Project of roughly 25 million dollars.

Of course, this is an over-simplification of the risk evaluation process, but it serves to underline the value that geologic, engineering and research work could yield in a number of areas. Such an analysis is presented here to build a case that a few dollars more spent in site investigation, design, and research, could result in major reductions in constructin cost and/or contingency -- a common goal for all projects and particularly important for publicly-funded, complex, underground works, where the uncertainties are high and the sponsors' tolerance for risk maybe limited.

5.4. LAr Cavern - Time to Construct

Time is also a key consideration for the construction of experiments. Not only can a faster construction timeframe provide a competitive edge to the physics collaboration, but it will also result in significant cost savings. Approximately half of the costs in the original underground estimate are time-related.

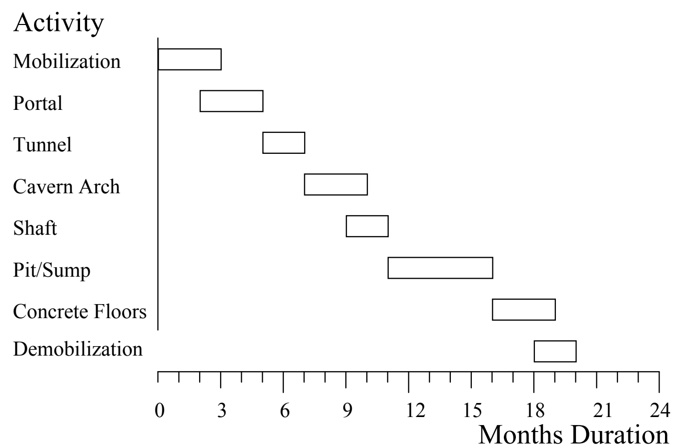

Figure 6: LAr Cavern - Critical Path Schedule

The construction schedule for the LAr cavern is shown in Figure 6. The construction of the LAr cavern can be completed in a two year timeframe. The critical path for a Long Baseline experiment associated with this particular detector would most likely pass through the construction activities at Fermilab. Under this scenario, and a number of other megadetector scenarios, there would be ample time to fully plan and integrate research tasks into the cavern construction program.

6. VALUE THROUGH RESEARCH

6.1. A Rock Mechanics Challenge

With construction costs of a shallow, medium-sized LAr cavern running at $25M and the unit cost range for deeper megadetectors estimated to be in the 500 to 1000 $/cubic meter range, the incentive to cut cavern costs through a combination of value engineering and research is great.

The challenge to rock mechanics and engineering communities is to identify the added value that the performance of discrete research tasks can bring to a cavern construction process. Below are listed a number of ideas aimed at reducing cost and risk and improving quality. The list is intended to serve as a prompt for further contributions and discussion.

6.2. *Requirements Setting*

Engineering insight into the technical and practical aspects of cavern construction is critical at this stage of the project, before concepts are committed to paper. It is important to document the design criteria, including a definition of key cavern flexibilities (size, shape, location) and cost-drivers. As part of this early brainstorming, the emergence of research targets and their potential risks and rewards to the Project can be identified.

6.3. *Site Investigation and Characterization*

Given the geo-variability of the site, the needs and benefits of a comprehensive site investigation campaign are self-evident. Ideally, research tasking can be identified to provide for an enhanced characterization of the sites, notably through the application of improved geophysics, geo-imaging, in situ probing, laboratory testing, geo-modeling technologies and the integrated use of probabilistic risk assessment techniques.

6.4. *Detailed Design & Modeling*

The design approach adopted for the DUSEL excavations will vary from site to site. Variations in the design process should reflect both the influence of rock mass heterogeneities and in situ stresses on mechanical stability. Models should be developed that can most accurately predict the full range of problem behaviors and support requirements during excavation and operation. Research in this area could support the optimization of ground support and study the influence of alternate rock engineering strategies on the short and long term comportment of the excavations, including pre-conditioning blasts, destress slots, pre-excavation support systems (cables, bolts, dowels..), excavation phasing (multi-pass shape, sizing and sequencing), excavation methods (controlled blasting, water-jet scaling, hydraulic hammer, roadheader), post-excavation support systems and liners (steel arches, shotcrete, cast-in-place or pre-cast concrete).

6.5. *Construction & Monitoring*

Given the limitations of current investigative and modeling practices, engineering predictions of ground behavior remain imperfect. Instrumentation is a vital element of any large excavation process. For DUSEL, instrumentation is yet another area where research can be cost-effectively integrated into the design to record in situ parameters pre-‘, syn-‘ and post-construction (stress, strain, temperature, water pressure etc..). Megacaverns offer the instrumentation industry an open invitation to use its collective geo-imagination to develop a new generation of tools for the industry based on newly available technologies.

DUSEL can also offer opportunities for the continued development of remotely-operated or robotic drilling, scaling, shotcreting, and haulage units, supporting the mining and civil industries in making the cavern and tunnel construction process safer and more cost-effective.

7. CONCLUSIONS

During the course of a century of mining, the mine geology and ground behaviors at the Homestake Mine have been studied to depth, in depth. A detailed 3-D model of the mine geology has been developed, an in situ stress profile estimated based on extensive in situ measurement and ground response to excavation predicted and observed on large scales.

Geologic and engineering studies, in situ measurement, and field observation all indicate that excavation conditions will vary markedly within and across geologic units and to depth. A thorough site investigation will be required to eliminate adverse ground conditions and identify and investigate candidate excavation sites.

A number of large excavation concepts are on the drawing board. The working assumption is that suitable megacavern sites can be found which will allow for the adoption of cost-effective construction solutions. However, pending the performance of confirmatory site investigation work, the construction contingency associated with such large permanent excavations must remain large.

The author believes that rock mechanics and engineering research targeted to reduce cost drivers and risk in the broad engineering process can both enable physics experimentation and lead to improved practices in hard rock construction.

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